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PRIOR FOREIGN APPLICATION(S)

			Priority Claimed
0101744.8	United Kingdom	26 February 2001	X Yes ___ No
(Application Number)	(Country)	(Filing Date)	
			___ Yes ___ No
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I hereby claim the benefit under 35 U.S.C. 119(e) of any United States provisional application(s) listed below.

PRIOR U.S. PROVISIONAL APPLICATION(S

(Application Number)	(Filing Date)
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I hereby claim the benefit under 35 U.S.C. 120 of any United States application(s), or 365(c) of any PCT international application designating the United States of America, listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States or PCT international application in the manner provided by the first paragraph of 35 U.S.C. 112, I acknowledge the duty to disclose information which is material to patentability as defined in 37 C.F.R. 1.56 which became available between the filing date of the prior application and the national or PCT international filing date of this application.

U.S. OR PCT PARENT APPLICATION(S)

(Application Number)	(Filing Date)	(Patent Number, if any)
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I hereby appoint the following registered practitioners to prosecute this application and to transact all business in the Patent and Trademark Office connected therewith: Thomas E. Smith, Registration No. 18,243; Dennis M. McWilliams, Registration No. 25,195; James R. Sweeney, Registration No. 18,721; William M. Lee, Jr., Registration No. 26,935; Glenn

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I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under 18 U.S.C. 1001 and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

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27FEB01 E609187-2 D01914
P01/7700 0.00-0104744.8

1.	Your reference	MJN/67480/000
2.	Patent application number *(The Patent Office will fill in this part)*	**0104744.8**
3.	Full name, address and postcode of the or of each applicant *(underline all surnames)*	ABB Offshore Systems Limited 2 High Street Nailsea Bristol BS48 1BS United Kingdom (GB)
	Patents ADP number *(if you know it)*	7692221001
	If the applicant is a corporate body, give the country/state of its incorporation	United Kingdom (GB)
4.	Title of the invention	SEISMIC DETECTION
5.	Name of your agent *(if you have one)*	PAGE HARGRAVE
	"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*	Southgate, Whitefriars Lewins Mead Bristol BS1 2NT
	Patents ADP number *(if you know it)*	05996483001
6.	If you are declaring priority from one or more earlier patent applications, give the country and the date of filing of the or of each of these earlier applications and *(if you know it)* the or each application number	Country / Priority application number *(if you know it)* / Date of filing *(day / month / year)*
7.	If this application is divided or otherwise derived from an earlier UK application, give the number and the filing date of the earlier application	Number of earlier application / Date of filing *(day / month / year)*
8.	Is a statement of inventorship and of right to grant of a patent required in support of this request? *(Answer 'Yes' if:* *a) any applicant named in part 3 is not an inventor, or* *b) there is an inventor who is not named as an applicant, or* *c) any named applicant is a corporate body.* *See note (d))*	Yes

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Priority documents	-
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Statement of inventorship and right to grant of a patent *(Patents Form 7/77)*	Two
Request for preliminary examination and search *(Patents Form 9/77)*	One
Request for substantive examination *(Patents Form 10/77)*	-
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11. I/We request the grant of a patent on the basis of this application.

Signature Page Hargrave Date 22.02.01

PAGE HARGRAVE

12. Name and daytime telephone number of person to contact in the United Kingdom

Mr M J Newstead (0117) 927 6634

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Statement of inventorship and of right to grant of a patent

The Patent Office

Cardiff Road
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26 FEB 2001

1.	Your reference	MJN/67480/000
2.	Patent application number *(if you know it)*	0104744.8
3.	Full name of the or of each applicant	ABB Offshore Systems Limited
4.	Title of the invention	SEISMIC DETECTION
5.	State how the applicant*(s)* derived the right from the inventor*(s)* to be granted a patent	By virtue of a contract of employment between the inventor and the applicant.
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7.		I/We believe that the person*(s)* named over the page *(and on any extra copies of this form)* is/are the inventor*(s)* of the invention which the above patent application relates to. Signature Date 22.02.01 PAGE HARGRAVE
8.	Name and daytime telephone number of person to contact in the United Kingdom	Mr M J Newstead (0117) 927 6634

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6502082002

Patents ADP number *(if you know it)*:

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SEISMIC DETECTION

The present invention relates to seismic detection, for example to seismic detection carried out down a bore-hole to detect and measure seismic activity as represented by particle velocity or particle acceleration.

It is already known to use, for such purposes, seismic detectors which have sensors oriented along three axes preferably at right angles to one another.

However, in such a detector, using three axial sensors, if one sensor (or the electronics associated with it) should fail, then the resulting two-component detector cannot give a representation of the three-dimensional movement which it is attempting to measure. Only a two-dimensional projection of this three-dimensional motion on to a plane can then be measured.

Also, the margin of error in such a three-axis detector is considerable since the 'error inflation factor' (i.e. the relationship between the error propagated from the measurement to the final estimate) is substantially 1 for each axis of a three-component system which means that for such a system the errors are compounded in the final estimates.

Moreover, there is no scope for cross-checking in such a three-axis detector.

GB-A- 2 275 337 describes a seismic detector comprising a sonde which includes a configuration of four sensors (typically accelerometers or geophones) mounted in an equi-angular tetrahedral configuration with respect to one another to deal with the above problems. The four-sensor arrangement provides for some redundancy in the system such that the failure of one sensor still allows particle motion to be reconstructed in three dimensions (3D) and furthermore some form of error determination can be made, neither of which can be effected by the conventional three-sensor system. However, there is no disclosure of the processing required to realise these advantages, nor the processing required to extract the required seismic information from the configuration.

According to the present invention, there is provided, a method of using a seismic detector including four seismic sensors having axes which are in a substantially tetrahedral configuration, each of the sensors being in a respective signal channel, the method including one or more of the following steps:

a) combining outputs from the sensors to check that their polarities are correct;
b) testing to ascertain if one of the sensors is not working and, if so, using the outputs from the other three sensors;
c) if all four sensors are working, using their outputs to obtain an indication of motion in three dimensions on a least squares basis;
d) checking that the outputs from the sensors are coherent; and
e) checking the gains (or sensitivities) of the four channels.

There will now be described an example of the present invention, namely the processing steps using a seismic detector including four tetrahedrally arranged sensors, each sensor being in a respective signal channel which could include an amplifier receiving the sensor's ouput. It should be noted that the conventional orthogonal sensor arrangement does not allow any of these processing steps. The processing steps include one or more of the following steps.

1/ SIMPLE POLARITY CHECKS

As there are more components than unknowns, combining them allows checking that the polarities of the sensors are correct. This is simply done by adding the outputs from the four sensors. When all the sensors are working correctly, the four outputs will add to zero because of the geometry of the sensors. This process cannot be applied in a conventional three-sensor configuration because, by definition, if sensors are orthogonal, then no cross-checking can be performed.

2/ SINGLE COMPONENT FAILURE

If any one of the sensors, fails it is possible to still reconstruct the full 3D-particle motion with around 80% of the reliability of a three-sensor orthogonal set. This is possible because the three remaining sensors still span the three dimensions, although they do not do so as efficiently as three orthogonally arranged sensors.

3/ LEAST SQUARES OPTIMUM 3D PARTICLE MOTION

The four-sensor configuration is over-determined. This means that there are more measurements than there are unknowns. The three-sensor orthogonal arrangement is an even-determined system, as there are the same number of readings as unknowns. For the four-sensor configuration, a "least squares" estimate of each reading can be formed. This is more accurate than just the single estimate that a 3-sensor system allows.

4/ FOUR COMPONENT COHERENCY

For each time sample, four readings are made for three unknowns, which means that it is over-determined, i.e. four data points and three unknowns. By making a least squares estimate of the signal values, a type of root mean square (rms) is formed for the signal misfit. The normalised misfit is termed the four-component coherence (4CC). When all the sensors are working correctly and a signal, which is large compared to the system's noise, is measured then the 4CC, or normalised rms, will tend to zero. This allows the system to be checked and can also be used to measure the onset of transient signals.

When no signal is present, but only incoherent noise, then the normalised rms is large. When a signal arrives, the four sensors give a coherent signal and the normalised rms becomes very small. As the signal fades back towards the level of the background noise, the normalised rms increases and so can be used as an objective measure of signal to noise.

The 4CC allows checking that all the sensors are functioning properly and so a quality check of the data on a sample-by-sample basis.

5/ GAIN RECOVERY

If the gain of one or more of the sensor channels has changed over time, it is possible to regain a least squares best estimate of the gains and so adjust the gains over time. As described above, the simple summing of the channels will, in the presence of a coherent signal, give an answer of zero. This process can be repeated for many samples and a set of simultaneous equations constructed where the unknowns are the relative gains of the four channels. There are two possible solutions of such a set of equations. The first solution, which always exists, is that all the gains are zero. If this is the only solution that exists, then this is interpreted as meaning that the gains are changing rapidly with time, i.e. the sensors and/or their amplifiers are not working correctly. The second solution gives the best least squares estimate of the relative gains of the channels. This estimate can then be used to reset the relative gains of the channels if they are found to have drifted over time.

The above processing is shown diagrammatically as a flow chart in Fig 1.

The mathematics typically required to effect the processing steps above is described as follows.

In the interests of clarity, some simplifications have been made. Firstly, as it is the configuration of the sensors rather than their response functions that is being analysed, it is assumed that they have perfect impulse responses. The reference frame is defined such that the axes are aligned with the sensors. In the case of the four-sensor tetrahedral configuration, a first sensor is aligned with the z-axis, a second is aligned in the x=0 plane and the remaining two sensors are arranged so that all the sensors have equal angles between them. The configuration may be as in GB-A- 2 275 337.

The recording situation for an orthogonal three-sensor detector can be written as:

$$\begin{vmatrix} Xr \\ Yr \\ Zr \end{vmatrix} = \begin{vmatrix} Xo \\ Yo \\ Zo \end{vmatrix} \qquad (1)$$

where Xr, Yr and Zr are the positional values of the particle motion in the earth and Xo, Yo and Zo are the positional values of the particle motion of the observed on the X, Y and Z sensors respectively. Equation (1) shows the recording situation as it is normally assumed to exist. More explicitly this may be written out as:

$$\begin{vmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{vmatrix} \begin{vmatrix} Xr \\ Yr \\ Zr \end{vmatrix} = \begin{vmatrix} Xo \\ Yo \\ Zo \end{vmatrix} \qquad (2)$$

or in matrix form:

$$A \quad x \quad = \quad b \qquad (3)$$

Once the problem is posed as in equation (2), it can be regarded as a trivial linear inverse problem. The inverse of the matrix A in equation (3), which is the identity matrix, is also the identity matrix. However in some cases the situation will not be this simple but is more likely to be:

$$\begin{vmatrix} E & 0 & 0 \\ 0 & F & 0 \\ 0 & 0 & G \end{vmatrix} \begin{vmatrix} Xr \\ Yr \\ Zr \end{vmatrix} = \begin{vmatrix} Xo \\ Yo \\ Zo \end{vmatrix} \qquad (4)$$

where E, F and G are unknown although they are likely to be around one (or minus one if the detector is wired incorrectly). It can be seen that if E, F and G are not all unity, the inverse of the matrix A is not the identity matrix. For the tetrahedral four-sensor detector configuration, the situation is different. Now the linear inverse problem is over-determined, as there are four equations and only three unknowns. The equation can be

written as:

$$\begin{vmatrix} 0. & 0. & 1. \\ 0. & 0.942809 & -0.33333 \\ 0.816496 & -0.471404 & -0.33333 \\ -0.816496 & -0.471404 & -0.33333 \end{vmatrix} \begin{vmatrix} Xr \\ Yr \\ Zr \end{vmatrix} = \begin{vmatrix} Ao \\ Bo \\ Co \\ Do \end{vmatrix} \qquad (5)$$

In equation (5) it can be seen that there are four observations (Ao, Bo, Co and Do) and three unknowns (Xr, Yr and Zr). The system is over-determined and as well as producing an estimate of the three unknowns, an estimate of the uncertainty (or error) can also be calculated.

Solving equation (5) using the generalised inverse (Menke, 1981) gives:

$$\begin{vmatrix} Xr \\ Yr \\ Zr \end{vmatrix} = \begin{vmatrix} 0. & 0. & 0.70710 & -070710 \\ 0. & 0.81649 & -0.40824 & -0.40824 \\ 0.86602 & -0.28867 & -0.28867 & -0.28867 \end{vmatrix} \begin{vmatrix} Ao \\ Bo \\ Co \\ Do \end{vmatrix} \qquad (6)$$

The singular value decomposition (SVD) method is used to derive condition number and singular values for equation (5). Properties of the matrix which are worthy of note are that, as with equation (2), the condition number is 1.0 but now the singular values are all 1.1547 rather than 1. This means that the final least squares estimates of Xr, Yr and Zr are more reliable than the individual measurements. The uncertainty in the values is reduced by a factor of 1.15.

ONE SENSOR FAILURE

The effect of a single sensor failing for the case of the three- and four-sensor configurations is now considered. For the three-sensor orthogonal configuration, the failure of a single sensor means that the 3D particle motion is lost. However, this is not the case for the four-sensor tetrahedral configuration. Considering equation (5), if to be

concrete we let the receiver D fail, Equation (5) can now be written as:

Active components:

$$\begin{vmatrix} 0. & 0. & 0. \\ 0. & 0.942809 & -0.333333 \\ 0.816496 & -0.471404 & -0.333333 \end{vmatrix} \cdot \begin{vmatrix} Xr \\ Yr \\ Zr \end{vmatrix} = \begin{vmatrix} Ao \\ Bo \\ Co \end{vmatrix} \qquad (7)$$

Failed component:

$$-0.816496 \quad -0.471404 \quad -0.333333 \qquad\qquad Do$$

The three by three matrix A now has the generalised inverse

$$\begin{vmatrix} 0.707106 & -0.707106 & 0. \\ 0.498248 & 0.408248 & -0.816497 \\ 0.577350 & 0.577350 & 0.577350 \end{vmatrix} \qquad (8)$$

The very existence of (8) means that the 3D particle motion can be reconstructed even when any one of the four sensors fails. For the tetrahedral configuration with one failed sensor, one of the singular values is reduced to 0.577 and the condition number increases to 2. The uncertainty in the estimated signal is now increased by 1.732. In other words, the estimated uncertainty is now twice that of the full tetrahedral configuration.

FOUR COMPONENT COHERENCE

As has been shown in the previous section, the four-sensor configuration means that the signal estimate of the 3D particle motion is a least squares estimate and the results form an over-determined system of equations. Incoherent and coherent signals can be distinguished from each other. This means that, for the four-sensor configuration, a residual, or misfit, can also be calculated. If all the signals of all the sensors agree, then

this misfit will be zero. This ideal is approached when all the sensors are working properly and a strong signal is detected on all the sensors, i.e. the signal to noise ratio is high. If, on the other hand, only random signals are detected on the four sensors or a sensor does not work correctly, then the misfit or residual will not be zero. Thus the normalised misfit, or one minus the normalised misfit, which is here termed 4CC coherency, is a useful measure of signal quality. The over-determined nature of the configuration can therefore be used to distinguish between incoherent and coherent signals.

In matrix form we write:

$$x = (A^tA)^{-1}\,A^t\,b \qquad (9)$$

where the matrices are as defined in equation (5), then:

$$e = b - \mathit{b} \qquad (10)$$

where *b* is the expected value resulting form the least squares estimate. Substituting into (7) gives:

$$e = b - Ax \qquad (11)$$

$$e = b - A(A^tA)^{-1}A^tb \qquad (12)$$

$$e = (I - A(A^tA)^{-1}A^t)b \qquad (13)$$

which simplifies to:

$$e = \begin{vmatrix} 0.25 & 0.25 & 0.25 & 0.25 \\ 0.25 & 0.25 & 0.25 & 0.25 \\ 0.25 & 0.25 & 0.25 & 0.25 \\ 0.25 & 0.25 & 0.25 & 0.25 \end{vmatrix} b \qquad (14)$$

It can be seen that the misfit is simply calculated by just adding the four recorded signals. The 4CC for the n^{th} sample is then defined as:

$$4CC\,(n) = 1 - e\,(n)/b\,(n) \tag{15}$$

Some examples of 4CC and its uses will now be illustrated.

Fig. 2 shows a typical microseismic event. The time scale is in milliseconds and the amplitudes are given in micro-g. Clear p-wave and s-wave arrival can be seen in Fig. 2 and are marked by upward pointing triangles below the traces. Fig. 3 shows the same data as Fig. 2 but now the four-sensor data has been transformed using equation (5) to give three orthogonal traces and the bottom trace is now the 4CC as defined by equation (15). Several features of the coherency are worth comment. The 4CC increases from around zero to one at the point the p-wave arrives. Thus 4CC can be used to help in accurate phase detection. The 4CC can be seen to reduce gradually toward the end of the trace, this giving some measure of the signal to noise ratio of the signal.

Fig. 4 shows the same data as Fig. 2 but now the signal on the vertical has been halved before the transformation was performed. Comparison of the bottom trace on Figs. 3 and 4 show the effect this gain mismatch has on the 4CC. The analyst is alerted to the fact that the data are not within calibration, which stops the data being misinterpreted, e.g. polarisation analysis would produce erroneous direction estimates.

Fig. 5 shows a similar case to that illustrated in Fig. 4 but now the polarity of the vertical has been changed. This is the same as multiplying the gain by minus one. Again, the effect on the 4CC is easily seen and corrective action can be taken.

GAIN RECOVERY

It is a property of the tetrahedral four-sensor configuration that, at any given time, the sum of the signals on the four sensors equals zero (Equation 5) when the signal is coherent, i.e. when the signal to noise ratio is large. This provides a useful way of

checking the performance of the system and recovering the gains or sensitivities of the sensor channels if they have changed from their initial values.

A simple set of linear equations can be set up for a trace with the four fixed but unknown gains (G1, G2, G3 and G4) of the sensor channels for samples 1, 2, 3, 4, etc. written as:

$$\left|\begin{array}{cccc} A1 & B1 & C1 & D1 \\ A2 & B2 & C2 & D2 \\ A3 & B3 & C3 & D3 \\ A4 & B4 & C4 & D4 \\ A5 & B5 & C5 & C5 \\ A6 & B6 & C6 & D6 \\ & & & \\ & \ldots\ldots & \ldots\ldots & \\ An & Bn & Cn & Dn \end{array}\right| \quad \left|\begin{array}{c} G1 \\ G2 \\ G3 \\ G4 \end{array}\right| = 0 \qquad (17)$$

for samples 1 to n. This can be re-written in matrix notation as:

$$Ax = 0 \qquad (18)$$

where the matrix A consists of the measured traces and x the four fixed but unknown gains or sensitivities.

This system of equations is known as a set of homogeneous equations. Homogeneous equations have either one or two solutions. The first solution, the trivial solution, which always exists is $x = 0$. For the four-sensor configuration, this can be interpreted as the gains all being zero. The second solution, the non-trivial solution, can only exist under the condition that A is rank deficient. For real data, A will not be perfectly rank deficient but may be close to rank deficient. Singular value decomposition can be applied to the matrix A to analyse it. If the matrix A is found to be rank deficient, then the relative gains may be optimally recovered. However, it should be noted that only

the relative values of the gains may be recovered. The total gain of the four-sensor channels may be normalised or one gain may be arbitrarily taken as being correct.

Singular value decomposition also has the advantage that the condition number of the matrix A is given and this indicates how close, numerically, the matrix A is to being rank deficient. Not only does the technique allow the recovery of the gains, but the suitability of the data to this type of analysis is also given. Hence if the gains are varying rapidly with time the analysis will show this and stop the user being misled. Fig. 6 shows the application of the gain recovery procedure described in the preceding paragraphs and how it affects the 4CC. The top trace shows the 4CC for the original data. The middle trace shows the 4CC after the gain of one of the traces is halved. The bottom trace shows the 4CC after the application of the gain recovery procedure using the homogeneous equation approach. The gains are recovered to within 5 percent of their original values for these data.

SUMMARY OF PROCESS ACHIEVEMENTS

(1) Sensor redundancy. The configuration is robust and, even if a sensor fails, the full three dimensional particle motion can be recovered.

(2) 4CC allows for signal quality to be assessed objectively and sensor malfunctions to be easily detected.

(3) 4CC aids in the accurate picking of p-wave phases.

(4) Unknown gains or changes in sensitivity can be accurately recovered while the instruments are still *in situ* and without recording being interrupted.

It is emphasised that the mathematics described above is an illustration only of a method of achieving processing steps according to the invention.

It will be appreciated that the processing steps may be carried out by data processing means using software or by hard-wired logic, for example.

Another aspect of the present invention is the addition to the four-sensor detector of an omni-directional hydrophone to remove the ambiguity of a received wave being in compression or dilation in any seismic event.

CLAIMS

1. A method of using a seismic detector including four seismic sensors having axes which are in a substantially tetrahedral configuration, each of the sensors being in a respective signal channel, the method including one or more of the following steps:

a) combining outputs from the sensors to check that their polarities are correct;
b) testing to ascertain if one of the sensors is not working and, if so, using the outputs from the other three sensors to obtain an indication of motion in three dimensions;
c) if all four sensors are working, using their outputs to obtain an indication of motion in three dimensions on a least squares basis;
d) checking that the outputs from the sensors are coherent; and
e) checking the gains (or sensitivities) of the four channels.

ABSTRACT

A method of using a seismic detector including four seismic sensors having axes which are in a substantially tetrahedral configuration, each of the sensors being in a respective signal channel, includes one or more of the following steps: combining outputs from the sensors to check that their polarities are correct; testing to ascertain if one of the sensors is not working and, if so, using the outputs from the other three sensors to obtain an indication of motion in three dimensions; if all four sensors are working, using their outputs to obtain an indication of motion in three dimensions on a least squares basis; checking that the outputs from the sensors are coherent; and checking the gains (or sensitivities) of the four channels.

(Fig. 1)

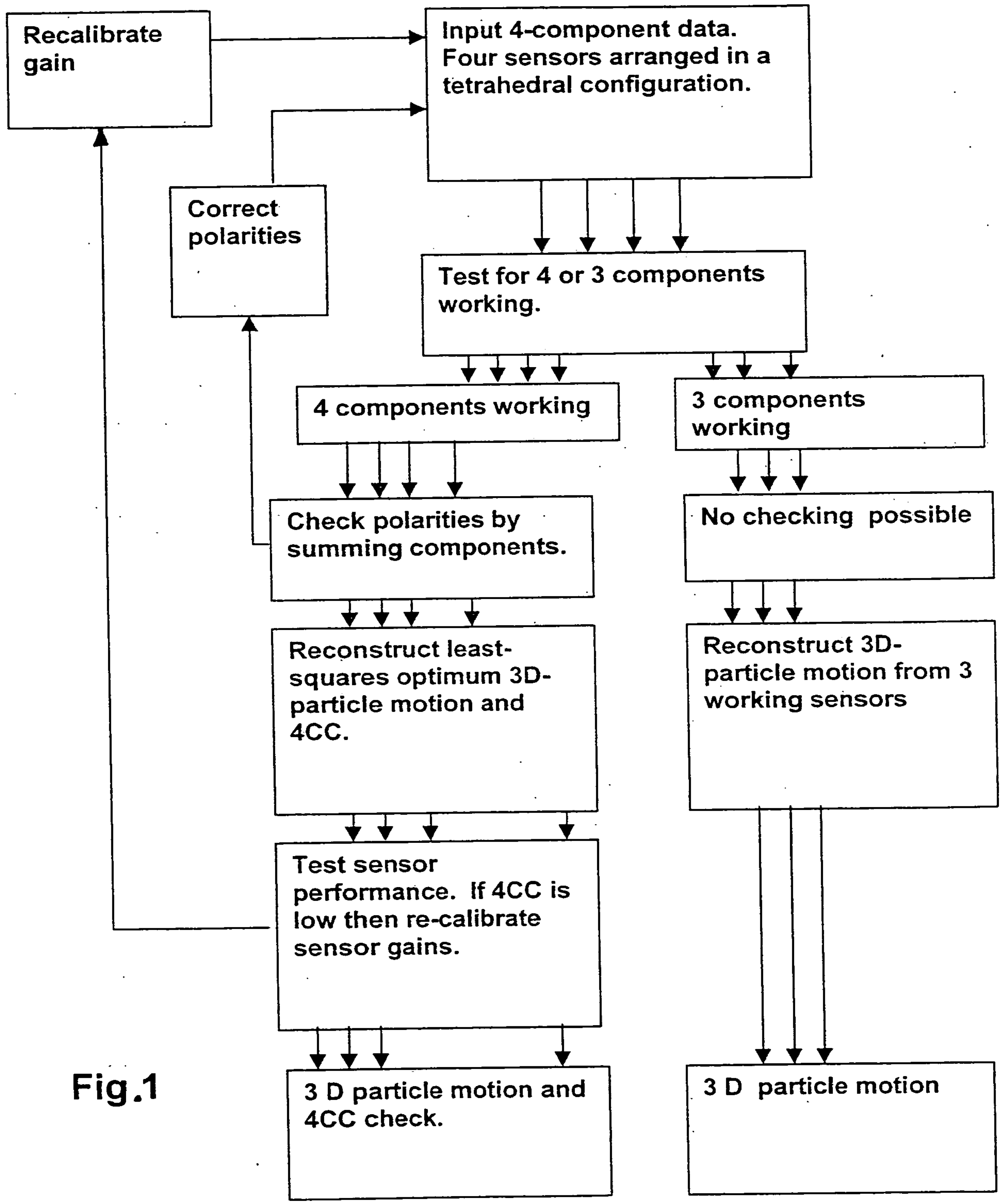
Recalibrate gain
Input 4-component data. Four sensors arranged in a tetrahedral configuration.
Correct polarities
Test for 4 or 3 components working.
4 components working
3 components working
Check polarities by summing components.
No checking possible
Reconstruct least-squares optimum 3D-particle motion and 4CC.
Reconstruct 3D-particle motion from 3 working sensors
Test sensor performance. If 4CC is low then re-calibrate sensor gains.
3 D particle motion and 4CC check.
3 D particle motion

Fig.1

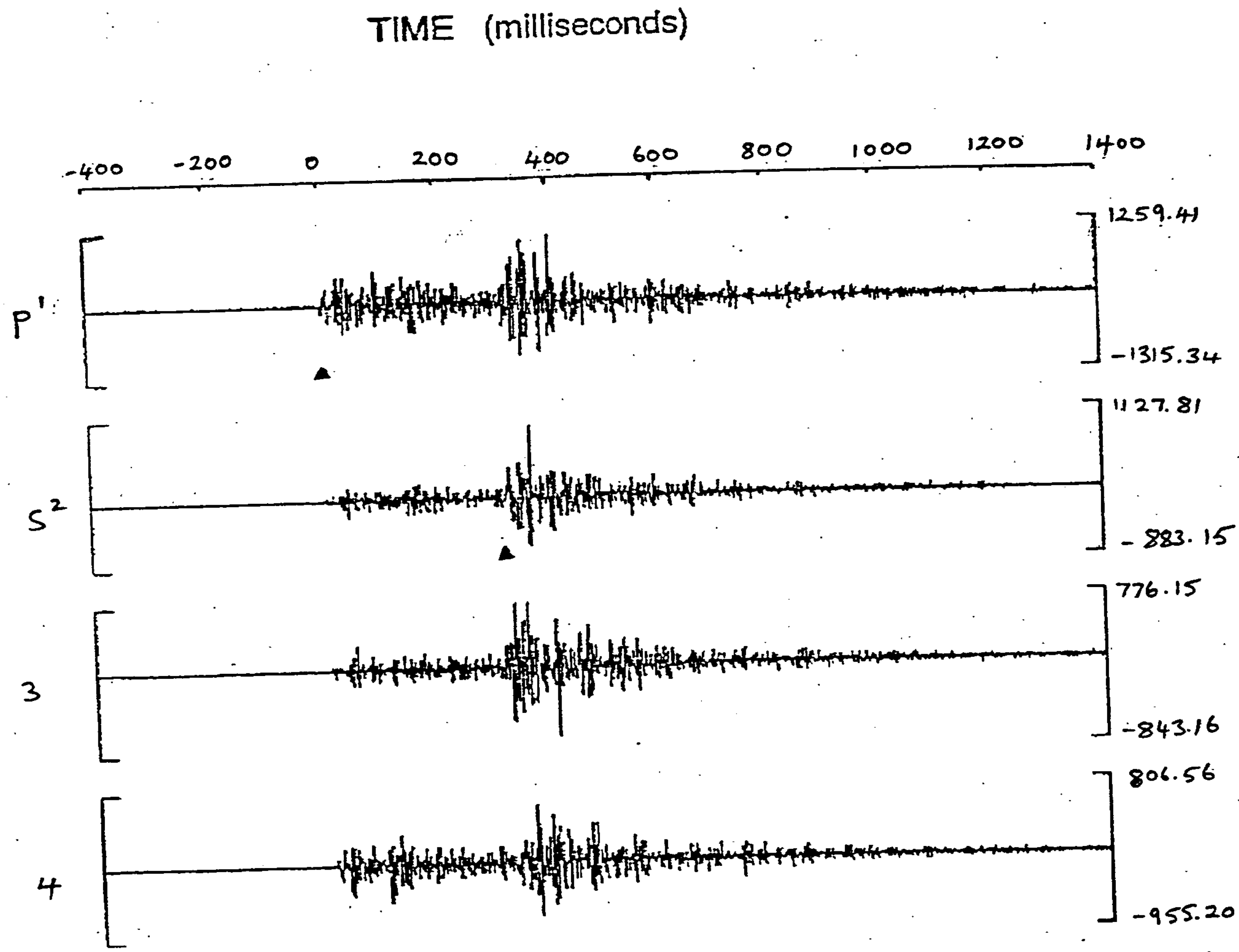
TIME (milliseconds)
-400
-200
0
200
400
600
800
1000
1200
1400
P'
1259.41
-1315.34
S²
1127.81
- 883.15
3
776.15
-843.16
4
806.56
-955.20

Fig.2

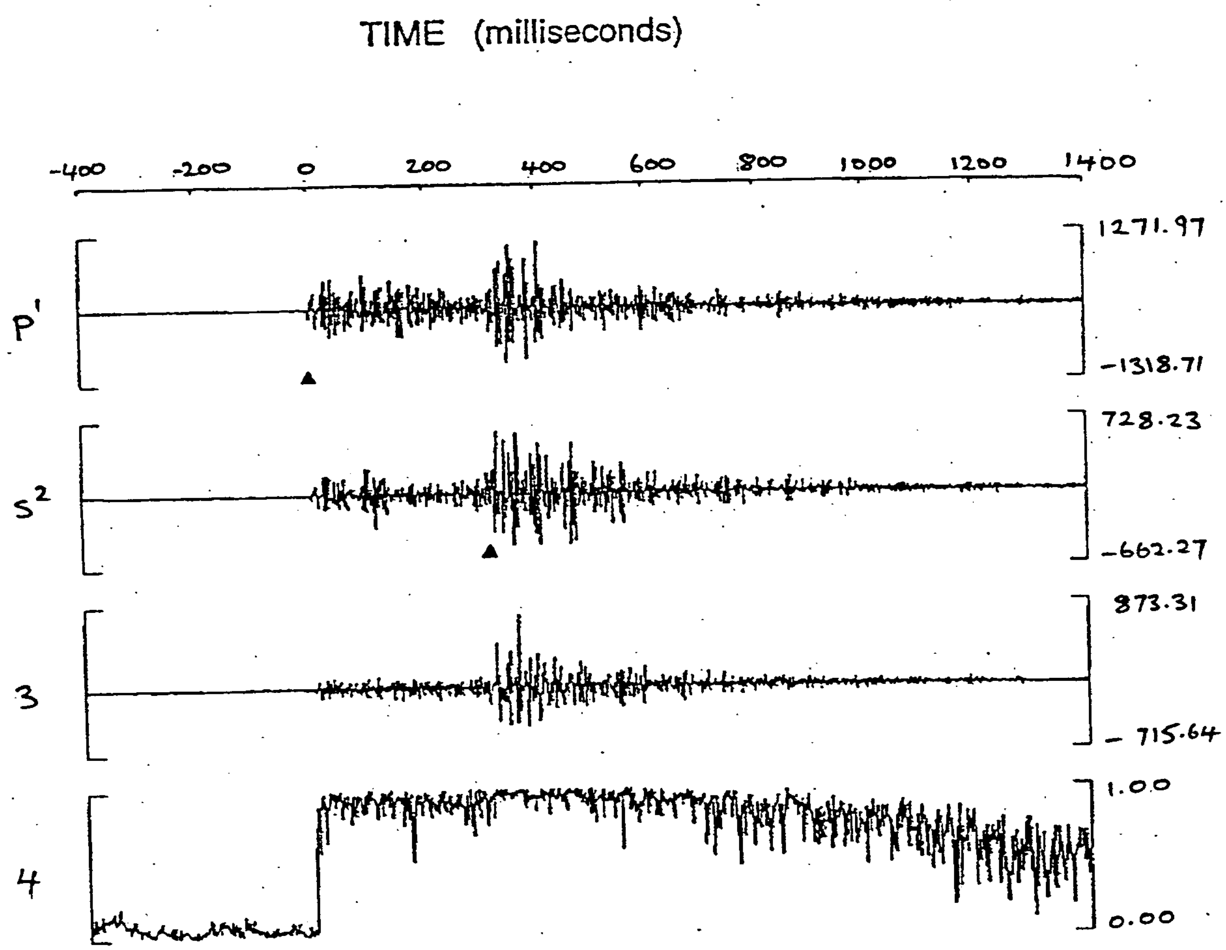
TIME (milliseconds)
-400
-200
0
200
400
600
800
1000
1200
1400
P'
1271.97
-1318.71
S²
728.23
-662.27
3
873.31
- 715.64
4
1.00
0.00

Fig.3

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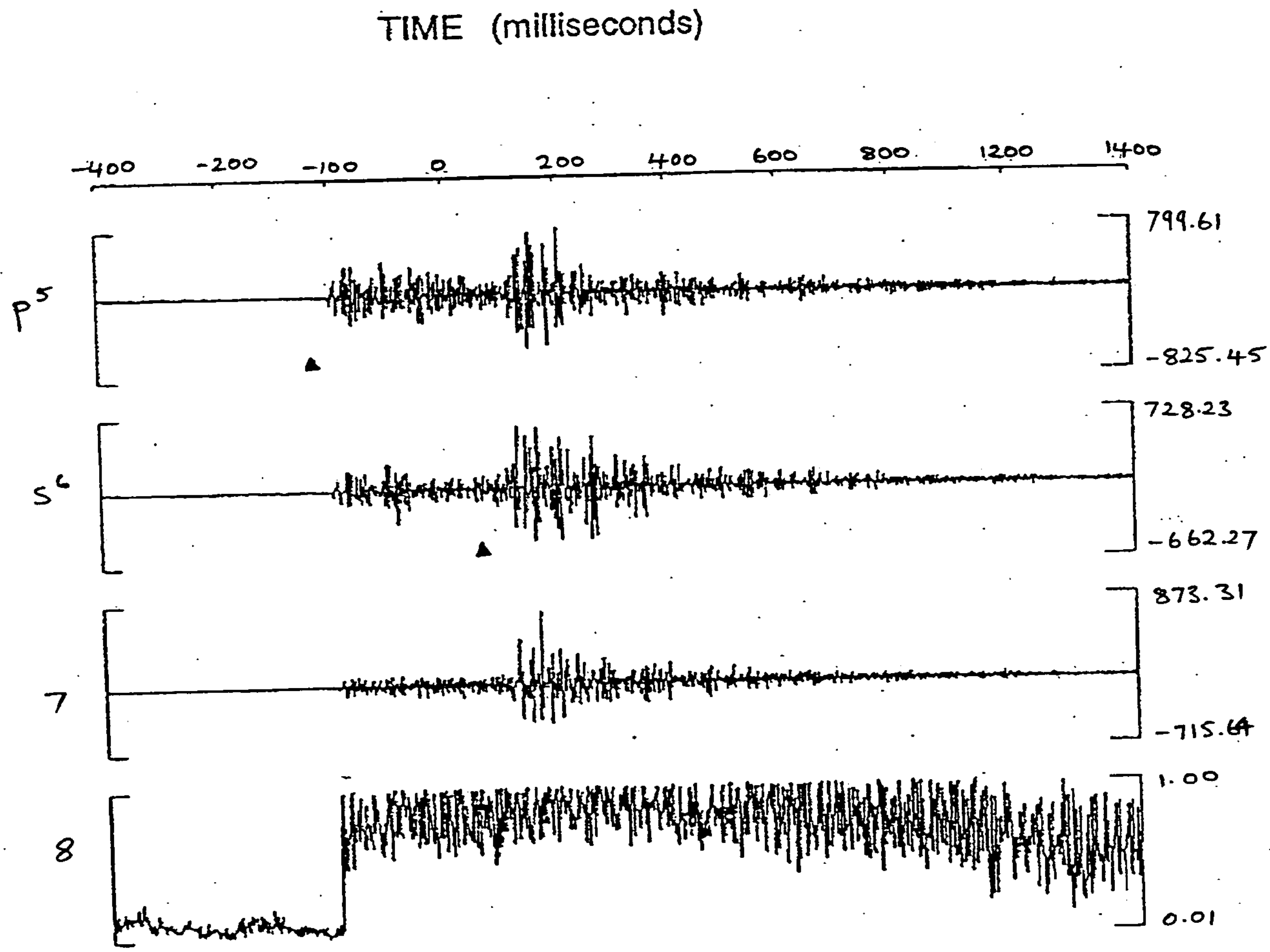
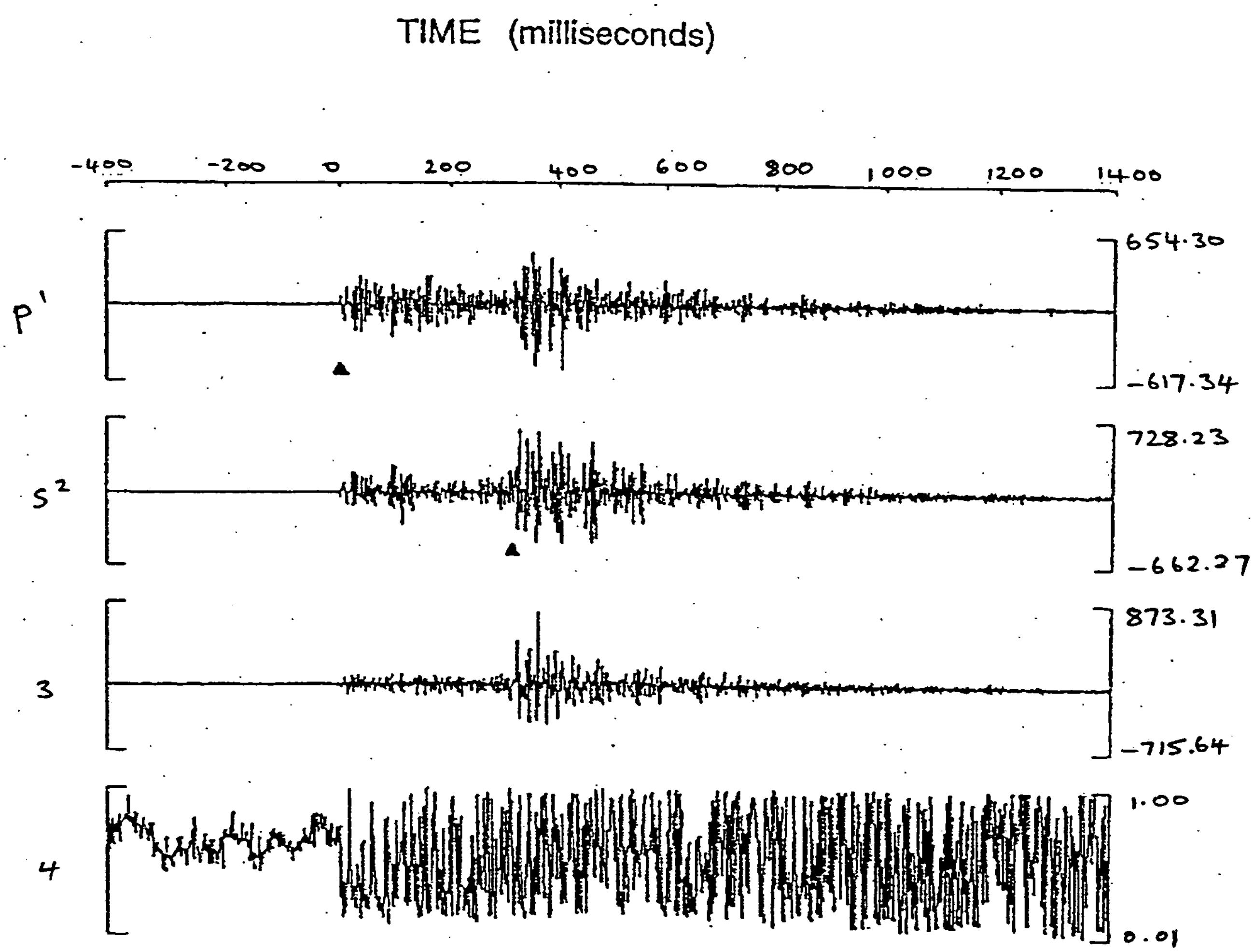

TIME (milliseconds)
-400
-200
-100
0
200
400
600
800
1200
1400
P5
799.61
-825.45
S6
728.23
-662.27
7
873.31
-715.64
8
1.00
0.01

Fig.4


TIME (milliseconds)
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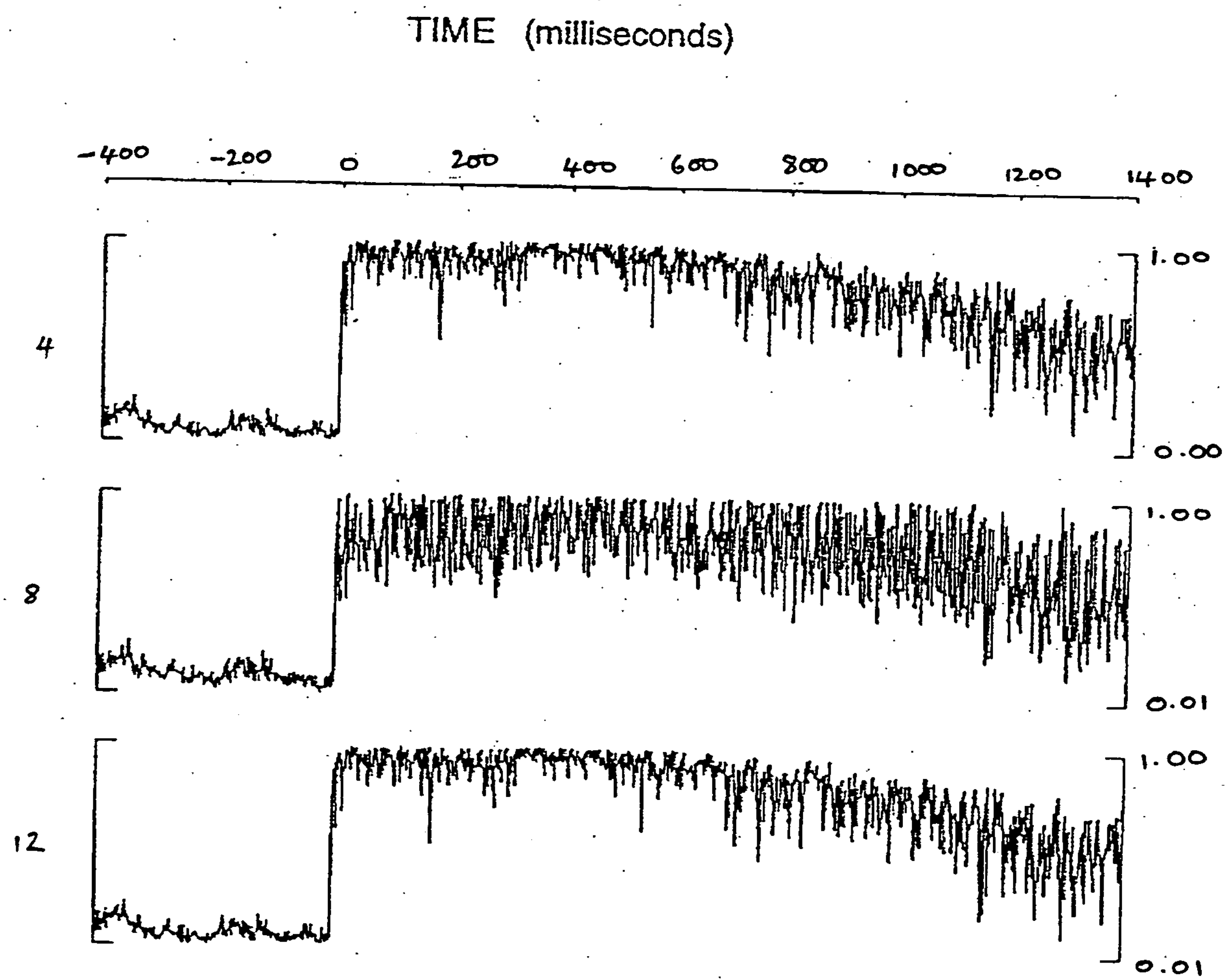
-200
0
200
400
600
800
1000
1200
1400
P'
654.30
-617.34
S²
728.23
-662.27
3
873.31
-715.64
4
1.00
0.01

Fig.5



TIME (milliseconds)
-400
-200
0
200
400
600
800
1000
1200
1400
4
8
12
1.00
0.00
1.00
0.01
1.00
0.01

Fig.6